

Search for electroweak SUSY production and Heavy Neutral Leptons at CMS



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ULB

Electroweak SUSY Production

Chargino $\tilde{\chi}_i^\pm$ and neutralino $\tilde{\chi}_i^0$:
Mixed states of Higgsinos and Electroweak gauginos

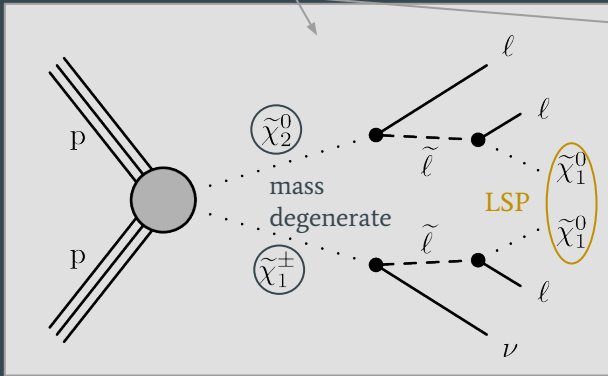
$$m(\tilde{\chi}_4^0) > m(\tilde{\chi}_3^0) > m(\tilde{\chi}_2^0) > m(\tilde{\chi}_1^0)$$

$$m(\tilde{\chi}_2^\pm) > m(\tilde{\chi}_1^\pm)$$

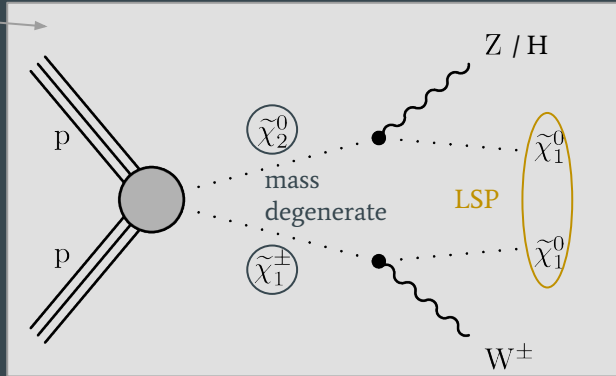
Multilepton search: signal models

- Search for production of **neutralinos** and **charginos**
- **R-Parity** conserved
- Simplified SUSY models
- Targets fully **leptonic** final states + **missing energy**
- <https://arxiv.org/abs/2106.14246> "SUS-19-012"

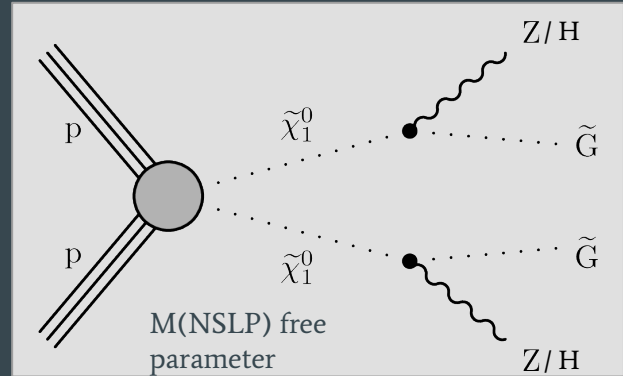
M(LSP) and M(chargino)
free parameters



Slepton-mediated decay



WZ/WH-mediated decay



Gauge Mediated SUSY breaking

- Sleptons too heavy
- **Leptonic SM boson** decay

- Gravitino LSP
- **Leptonic SM boson** decay

Strategy and selection of multilepton search

Search categories defined according to final states

Final State	Sensitive models
2 SS leptons	"compressed" scenarios Small δm between SUSY particles
3 light leptons, no OSSF	nonresonant lepton production from H decay
3 light leptons, OSSF	flavor democratic
3 leptons including tau	tau enriched tau dominated
4 leptons	Gauge mediated SUSY breaking

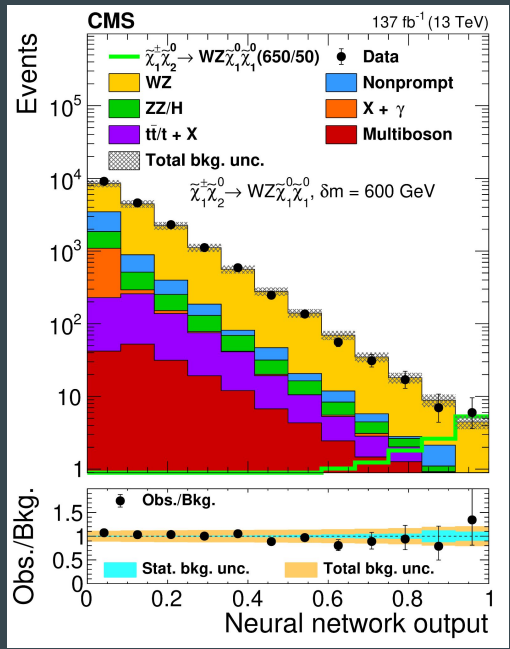
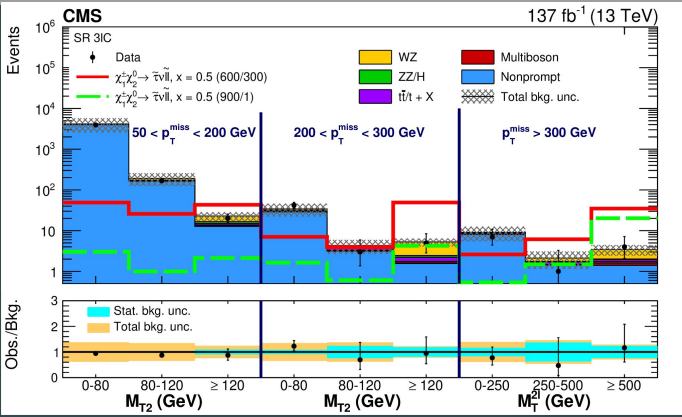


3 light leptons, OSSF

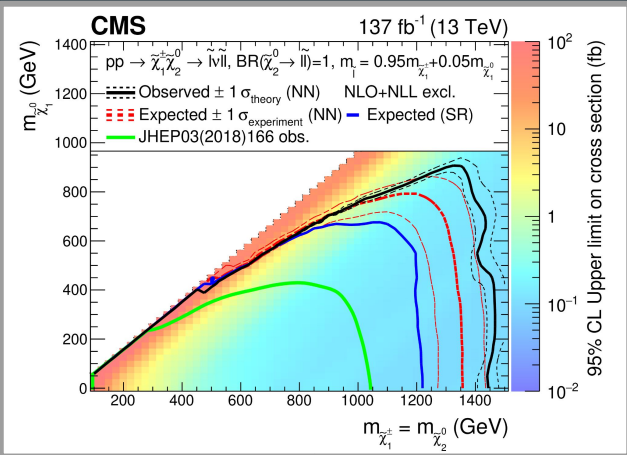
- Highly sensitive to **flavor democratic**
- Large background from SM

Parametric NN

- Trained for:
 - Slepton mediated
 - WZ-mediated
- Parameter: $\delta m = M(\text{chargino}) - M(\text{LSP})$
- δm driving factor for kinematics

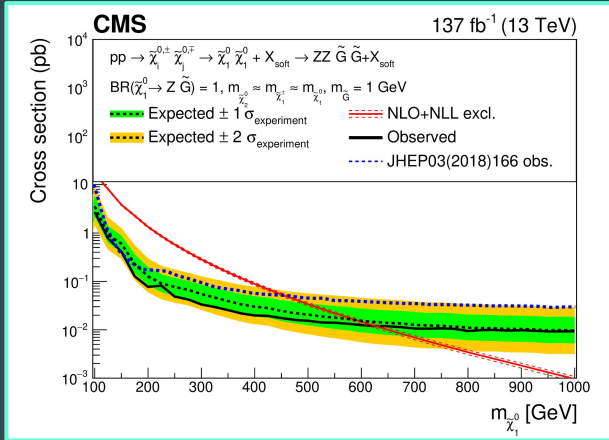
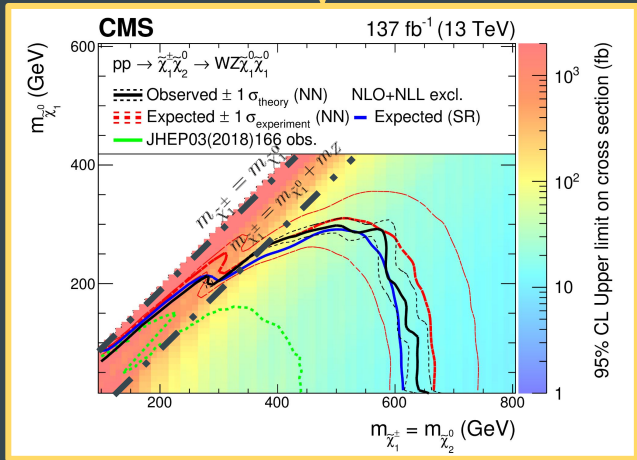


Interpretation of multilepton SUSY search results



No significant excess observed

WZ-mediated:
 WZ corridor has been closed



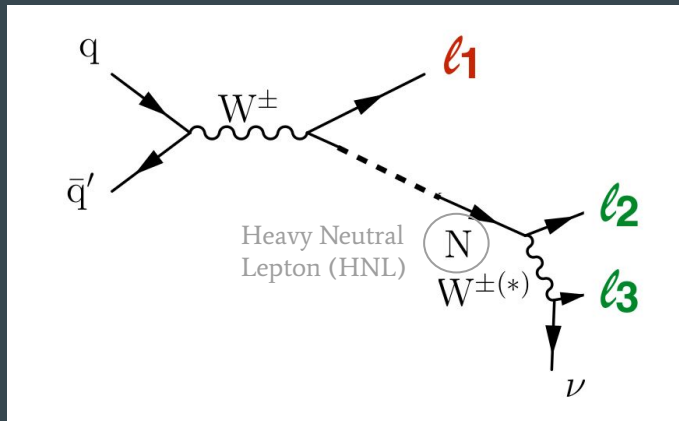
“Flavor democratic”
 slepton mediated
 Major improvements from
 full Run II and NN

GMSB ZZ-mediated

Search for Heavy Neutral Leptons

Heavy Neutral Leptons

- No direct interactions with sterile HNL
- Interactions through mixing of HNL with SM neutrinos



- HNL production in decays of W bosons
- Depending on the mass of the HNL, different scenarios arise

Low Mass: $m(N) < m(W)$
 W from HNL decay off-shell

- $1 \text{ GeV} < m(N) < 15 \text{ GeV}$:

$$\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$$

- Long-lived HNL
- Displaced Leptons

- $10 \text{ GeV} < m(N) < 80 \text{ GeV}$:
 Prompt HNL

High Mass: $m(N) > m(W)$
 First W off-shell

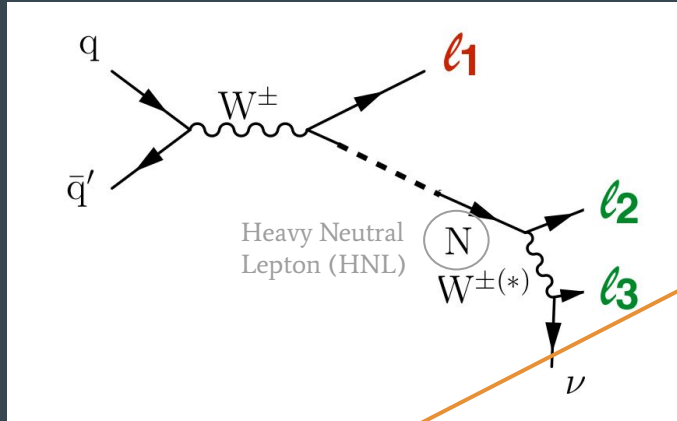
- $80 \text{ GeV} < m(N) < 1500 \text{ GeV}$

Ongoing Full Run II HNL analyses:

- **Long-lived** HNL (displaced)
 - **Trilepton** final state ([EXO-20-009](#))
 → UGent
 → Results are public and about to publish
 - **Two same sign lepton** final state ([EXO-21-011](#))
 → UGent, UCL, Antwerp
 → Almost final
- **Short-lived** HNL (prompt): UGent-ULB
 - Previous iteration with 2016 data: [EXO-17-012](#)
 - Now adding **tau coupling!**

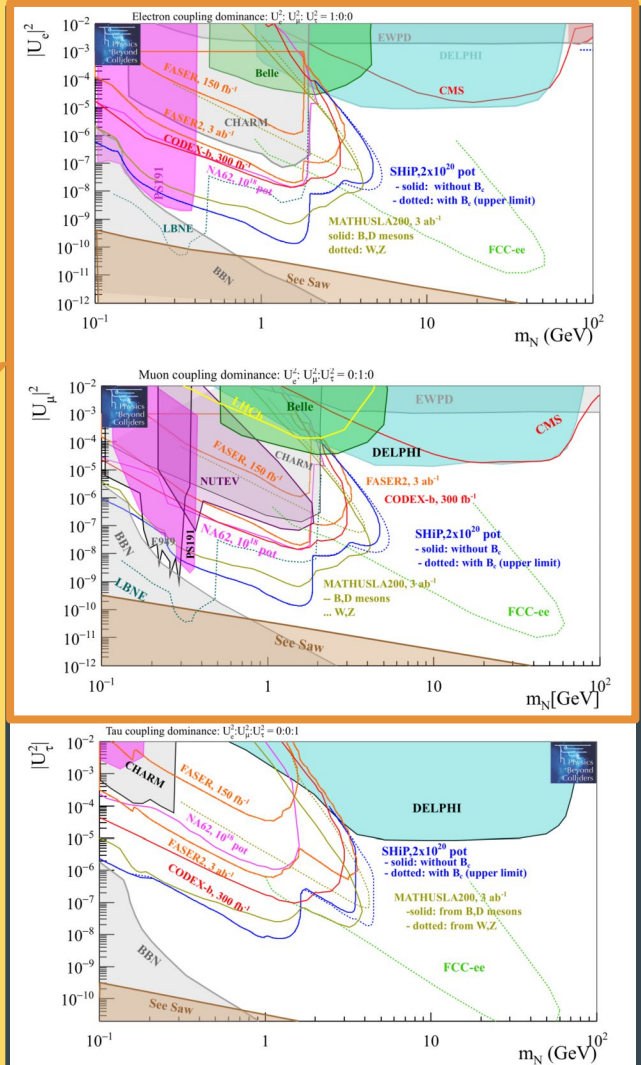
Heavy Neutral Leptons

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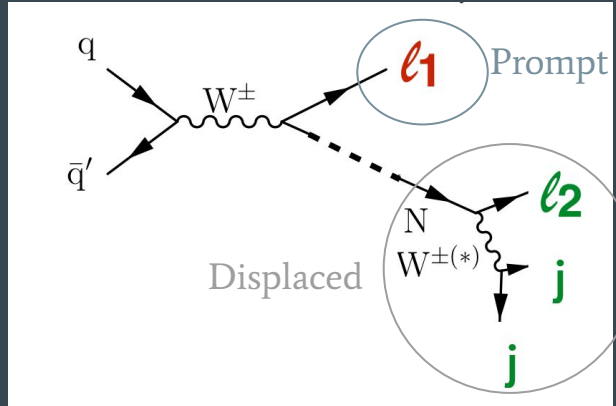


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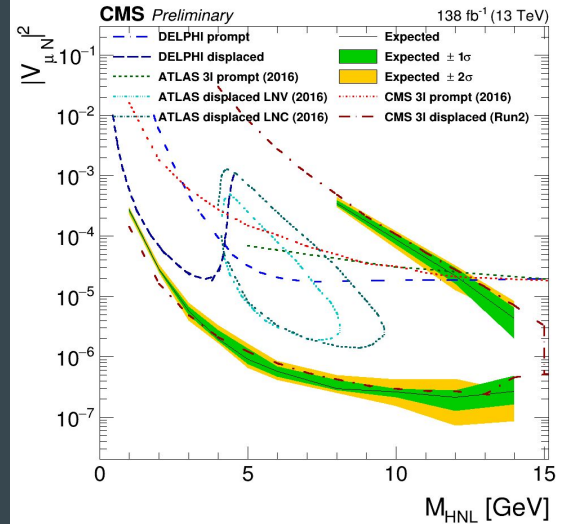
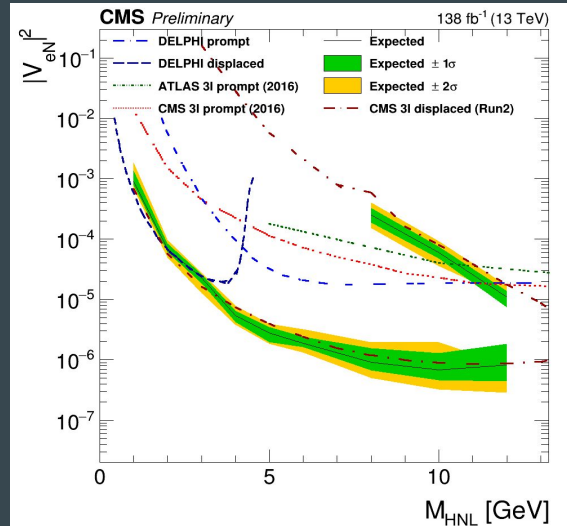
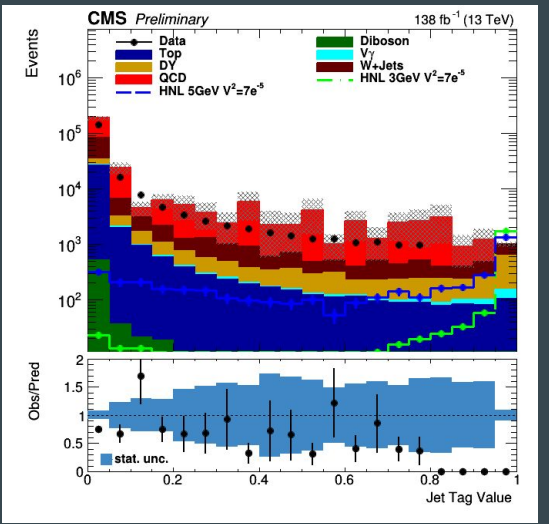


Displaced dilepton analysis

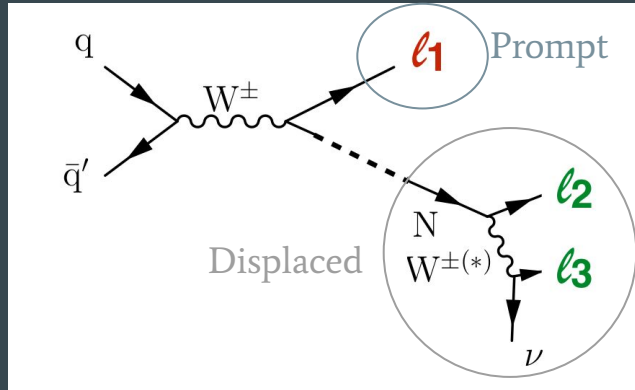


- Binned likelihood fit to search regions
- Expected limits compared to prompt and displaced trilepton

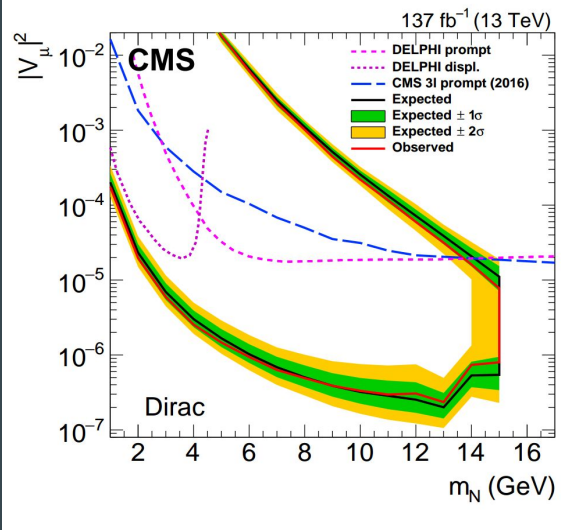
- Large background: (i.e. displaced leptons from hadron decay)
 - Particle Flow Network (PFN) trained: 2 dense neural networks
- PFN used in background estimation and signal region definition



Displaced trilepton analysis

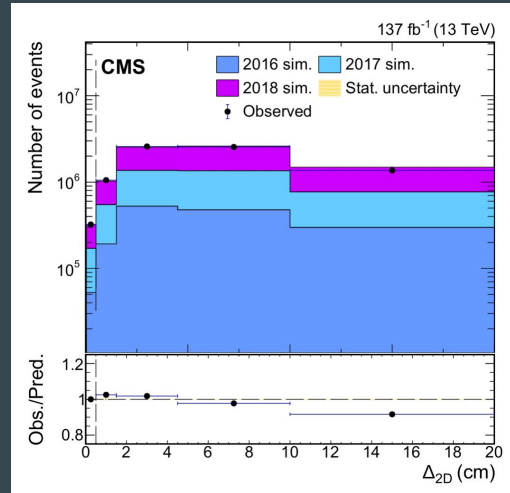
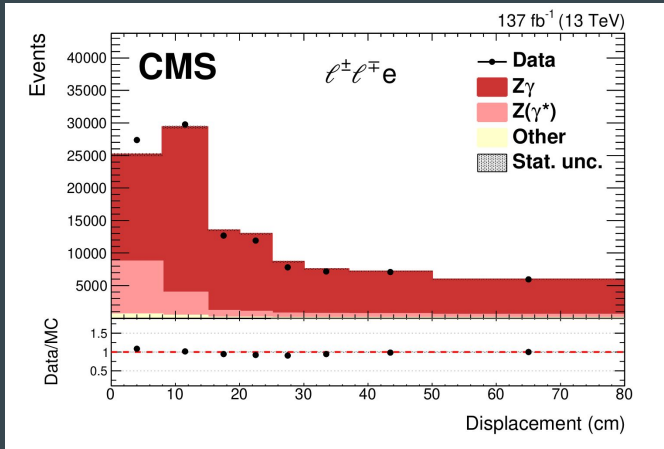


- Trilepton final state previously explored in [EXO-17-012](#): Prompt final states
- Now extended to lower $m(N)$ sensitivity with displaced leptons
- Results are public: [PAS](#)
- **No excess** observed



Innovative techniques for estimation of **tracking reconstruction** and **SV efficiency**

- Left: electron reconstruction and identification study in $Zg(*)$
- Right: Efficiency validation using $K_S^0 \rightarrow \pi^\pm \pi^\pm$



Prompt HNL analysis: Strategy and challenges

Only used
in high-mass

Categories

	I1	I2	I3	Name
1	$\tau_h^{\pm\pm}$	$\tau_h^{\pm\pm}$	l	SS $\tau+l$
2	$\tau_h^{\pm\pm}$	$\tau_h^{\pm\pm}$	l	OS $\tau+l$
3	$\tau_h^{\pm\pm}$	l	l	OS $l+\tau$
4	l^\pm	$\tau_h^{\pm\pm}$	l^\pm	SS $l+\tau$
5	e	e	e	eee
6	μ	μ	μ	$\mu\mu\mu$
7	e	e	μ	ee μ
	e	μ	e	
8	e	μ	μ	e $\mu\mu$
	μ	e	μ	
	μ	μ	e	

1 - 8

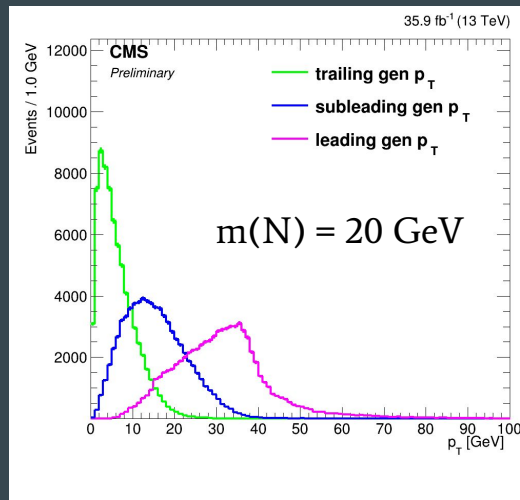
Sensitive to ν_τ
coupling

5 - 8

Sensitive to ν_e/ν_μ
coupling

Soft leptons at low HNL masses:

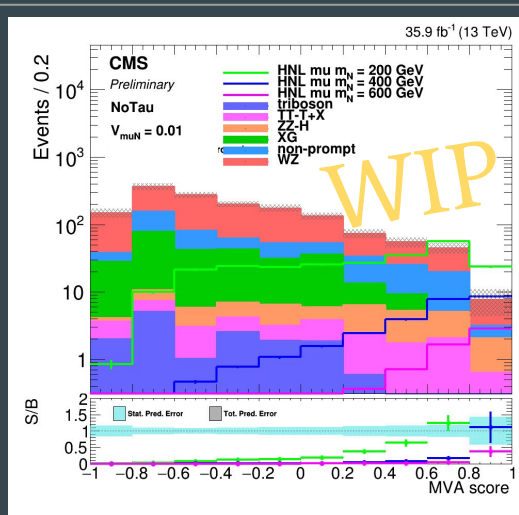
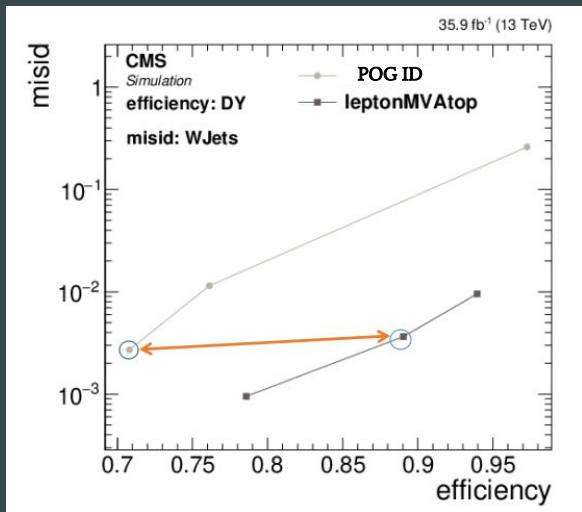
- **Inclusive trigger strategy** (single lepton, dilepton and trilepton triggers)
- Corresponding object selection



Prompt HNL analysis: Improvements and results

Improved Object Selection:

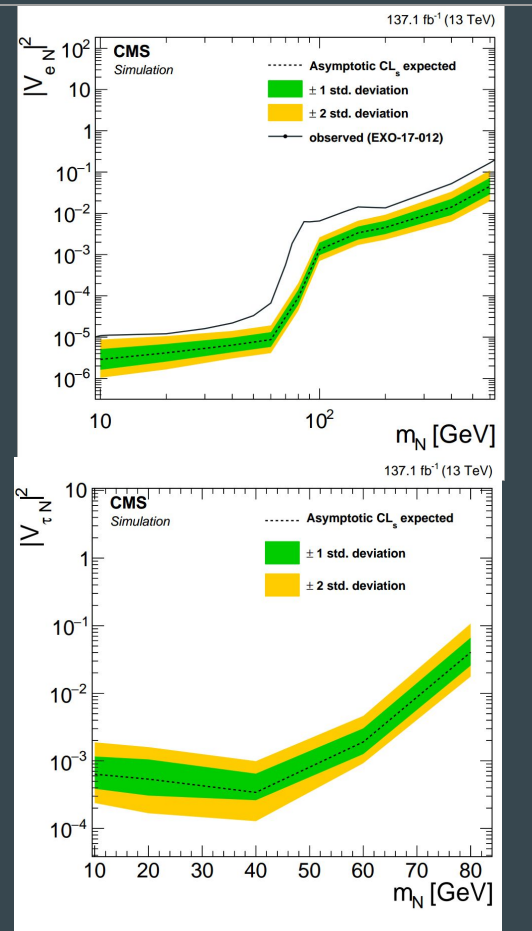
- New in-house MVA developed by Ghent CMS group
- Increase in efficiency per lepton of 20%



Improved signal selection:

- Training MVA for low and high mass regions
- Specialized signal samples with gen filters for optimal sample size

Currently switching to UL



Conclusions

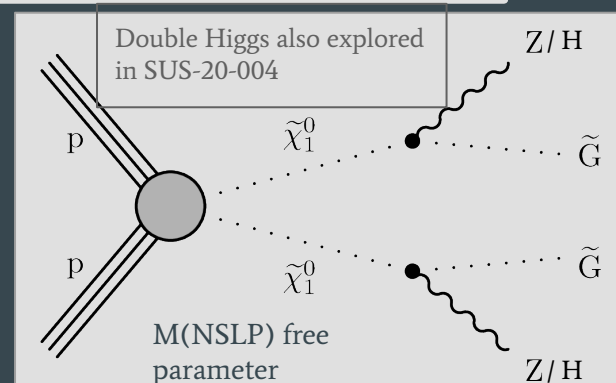
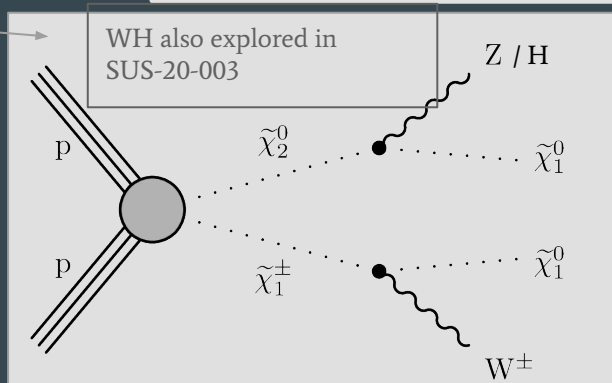
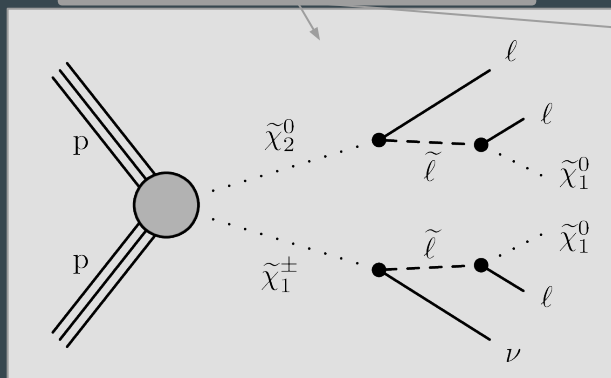
- Presented analysis searching for **electroweak production of SUSY** using **full Run II** data
- **No significant excesses** observed
- Presented HNL searches in CMS
- **Displaced HNL** searches are nearing final stages
- **Prompt HNL search**, which will close the circle, is switching to UL

BACKUP

SUS-19-012: signal models

M(LSP) and M(chargino)
free parameters

- Search for production of **neutralinos** and **charginos**
- **R-Parity** conserved
- Simplified SUSY models
- Targets fully **leptonic** final states + **missing energy**
- <https://arxiv.org/abs/2106.14246>



- **Different flavor scenarios** depending on composition of chargino/neutralino:
 - **“Flavor democratic”**: Equal probability for all lepton flavors
 - **Tau enriched**: Chargino decay favors taus
 - **Tau dominated**: Exclusive decay to taus

- Sleptons too heavy
- Forced decay to SM bosons and LSP
- **Leptonic SM boson** decay
- BR $\sim 3\%$: Much lower than slepton mediated decay

- **Gauge Mediated SUSY breaking**
- Higgsino-like chargino/neutralino
- \sim massless gravitino
- \sim mass degenerate charginos/neutralinos
- **Effective NLSP** production

SUS-19-012: Backgrounds

Estimated from simulation and validated in control regions in data:

- WZ: Additional validation of MT distribution for effects from:
 - mispairing of leptons
 - MET resolution
- ZZ
- tX/ttX
- Triboson
- Internal/external conversion

4 Types of SM backgrounds.

- SM events with 3 or more prompt leptons or SS dilepton
- External and internal conversions of photons
- Nonprompt backgrounds
- Charge mismeasurement

Estimated using data-driven “tight-to-loose” method:

- Main contributions:
 - ttbar
 - DY
- Light lepton ratio measured in single lepton QCD-enriched events
- Tau ratio measured separately for tt and DY control regions
- Background estimation from applying ratio to “sideband” of SR where one or more leptons fails tight selection
- Tau: ttbar or DY ratio applied depending on major contribution in the SR

Electron sign misid probability from simulated DY, ttbar and diboson production

- Validated and normalized in DY control region

Muon sign misid probability found negligible in MC
→ Estimated from MC

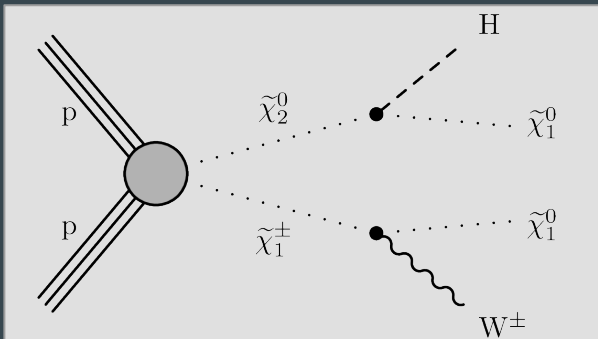
SUS-19-012: Strategy and selection

Search categories defined according to:

- Number of leptons
- Flavor content
- OSSF pairs

3 light leptons, no OSSF

- Sensitive to **nonresonant lepton production** from H decay
- Targets $H \rightarrow WW$ (BR $\sim 20\%$)
- SRs binned in $\min(\Delta R(l, l))$



3 light leptons, OSSF

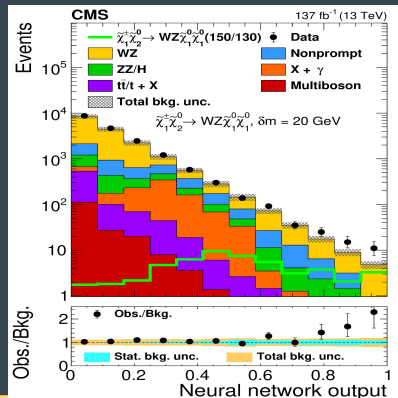
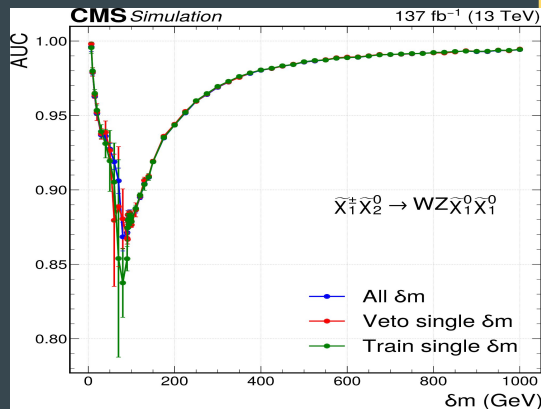
- Highly sensitive to **flavor democratic**
- Large background from SM
- 2 strategies:
 - A set of SR
 - **Parametric Neural network**

Parametric NN

- Parametric in $\delta m = M(\text{NLSP}) - M(\text{LSP})$
- Relatively small difference between different mass points but equal δm
- Training for slepton mediated (for 3 different slepton mass points) and WZ decay models

Set of SRs:

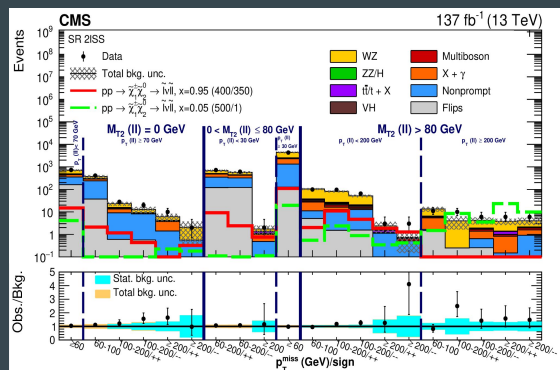
- Binned in MT, missing transverse energy, HT and $M(l, l)$



SUS-19-012: Strategy and selection

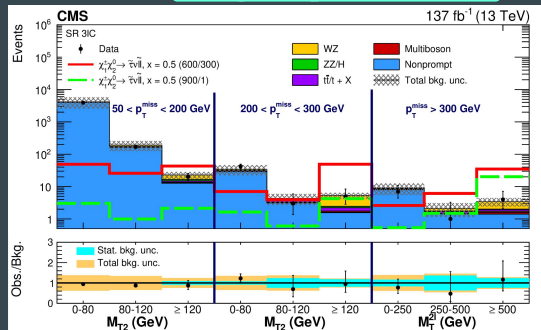
2 lepton, same sign

- Sensitive in “**compressed**” scenarios (soft leptons):
 - Small δm
 - slepton mass close to NSLP or LSP mass
- SRs binned in MT_2 , $p_T(l, l)$, missing transverse energy



3 leptons, $\geq 1 \tau$

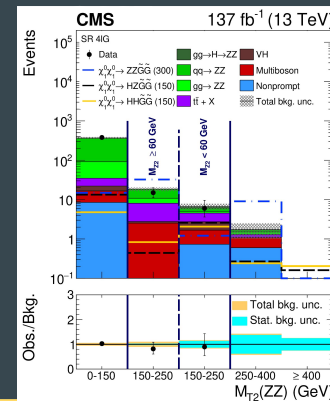
- Sensitive to **right-handed sleptons** and scenarios where other sleptons are **too heavy**
- SR strategy for different final states:
 - OSSF light leptons + tau
 - OSOF light leptons + tau
 - SSOF light leptons + tau
 - 1 light lepton + 2 taus



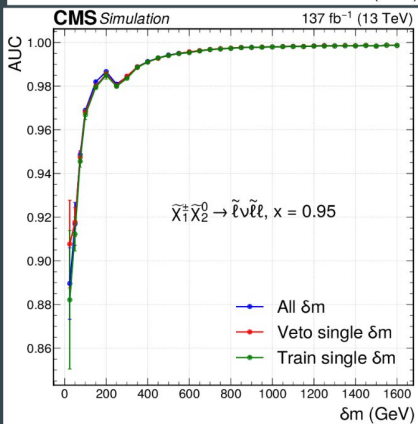
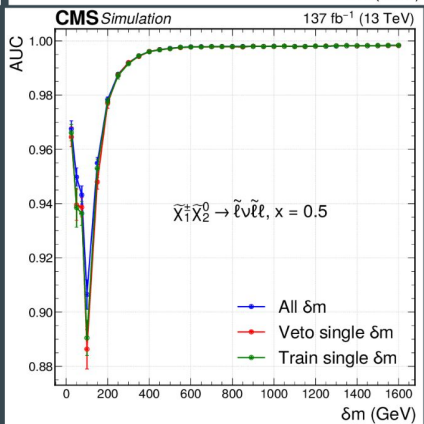
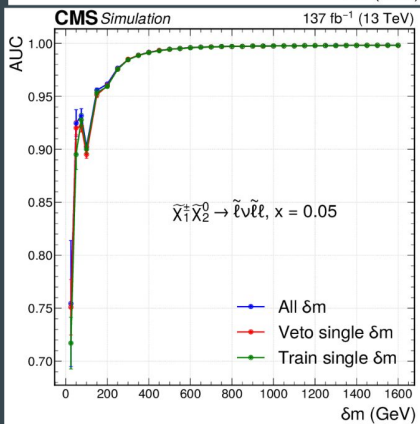
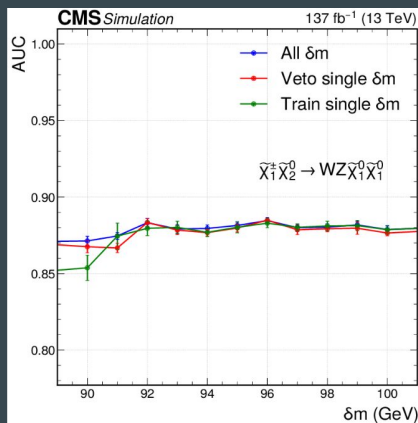
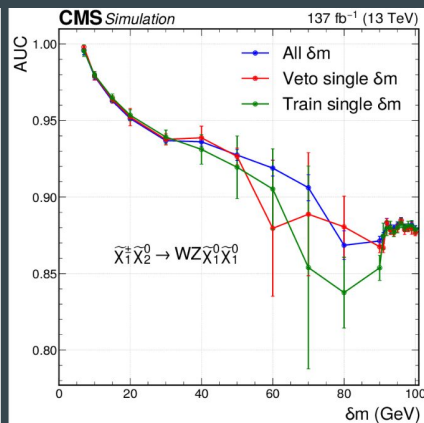
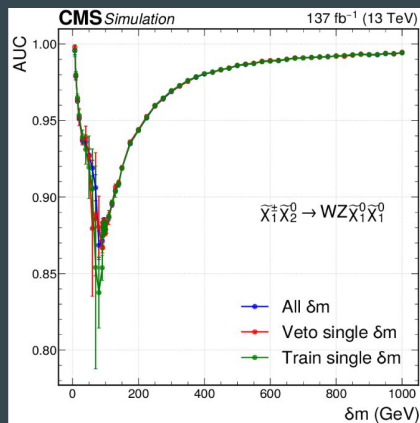
4 leptons

- Sensitive to **gauge mediated** models
- SRs for different final states:
 - 4 light leptons, 2 OSSF
 - 4 leptons including taus or without 2

Targets decays with 2 Z bosons



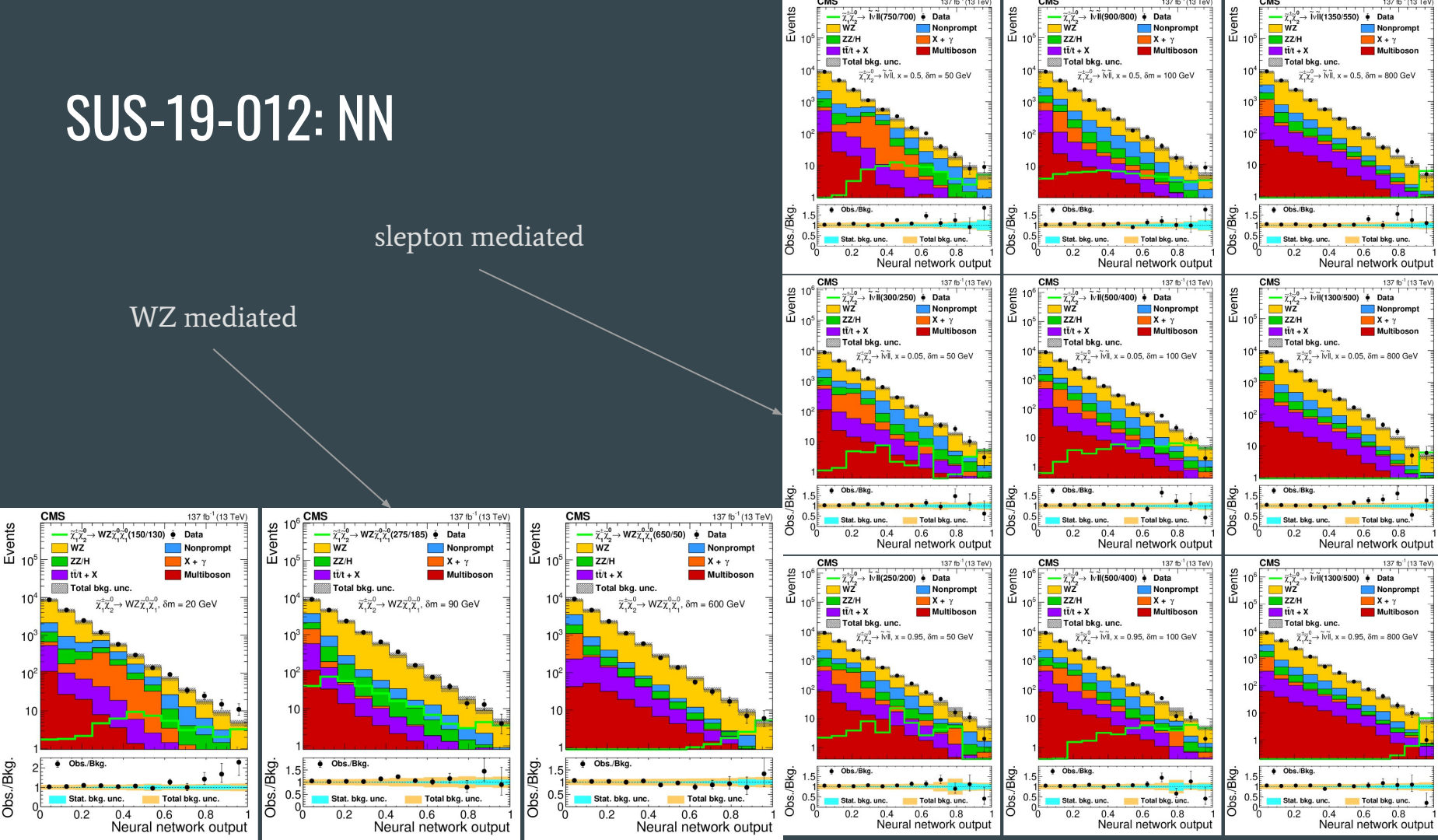
SUS-19-012: NN



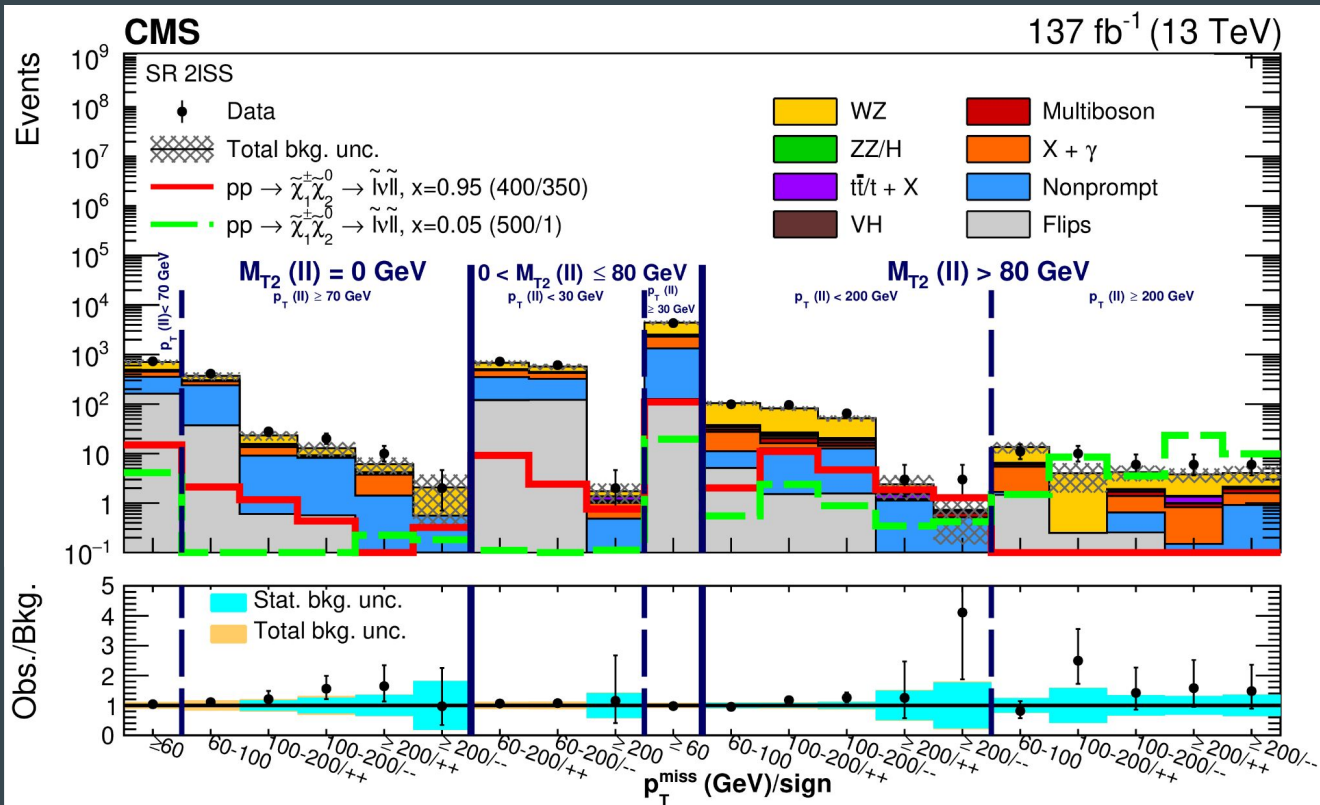
SUS-19-012: NN

stlepton mediated

WZ mediated



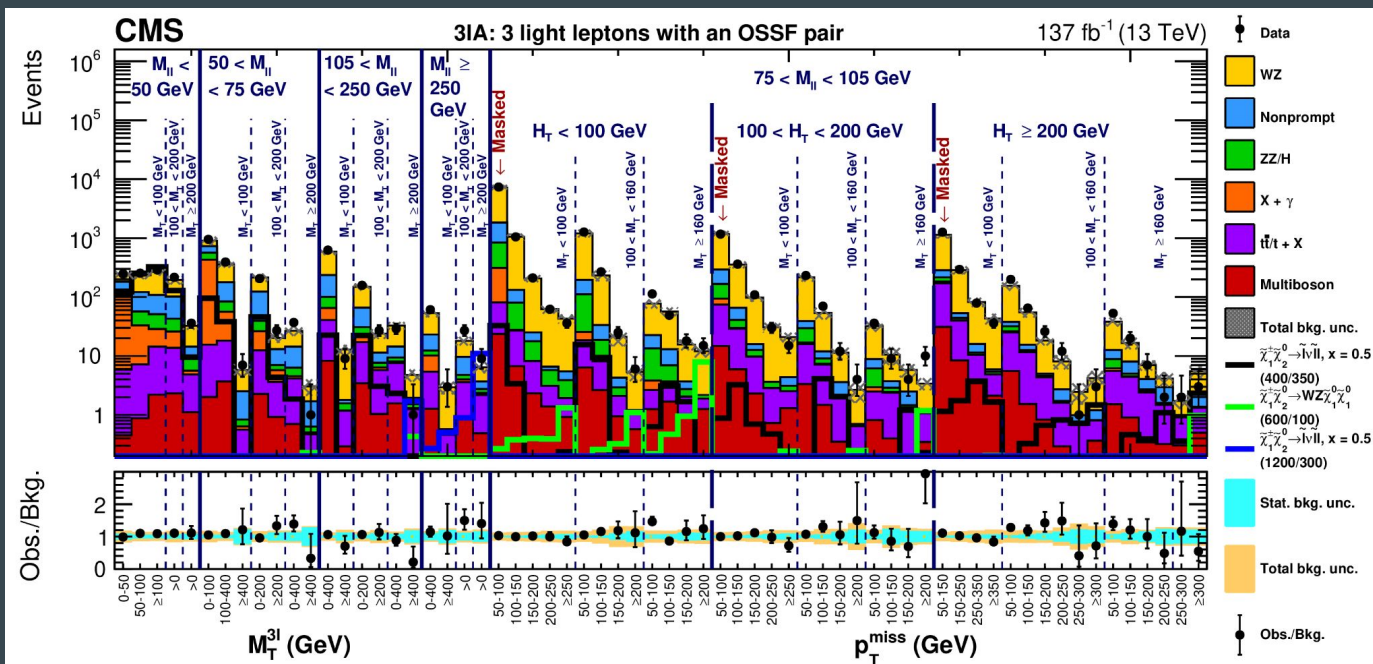
SUS-19-012: Search Regions



2 same sign light leptons

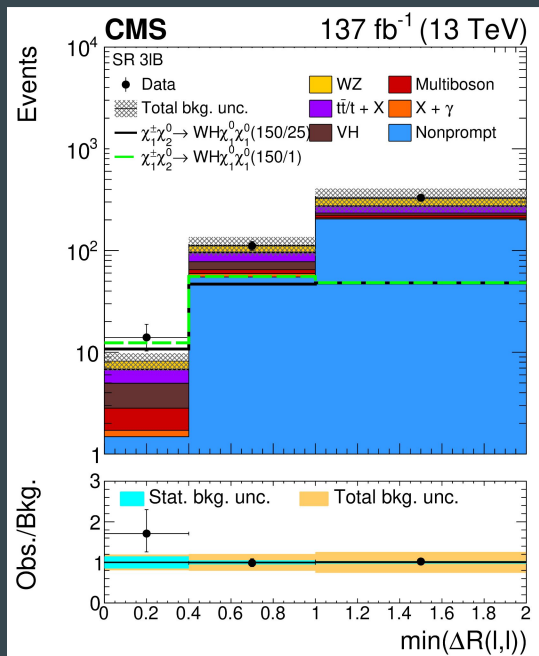
“2ISS”

SUS-19-012: Search Regions

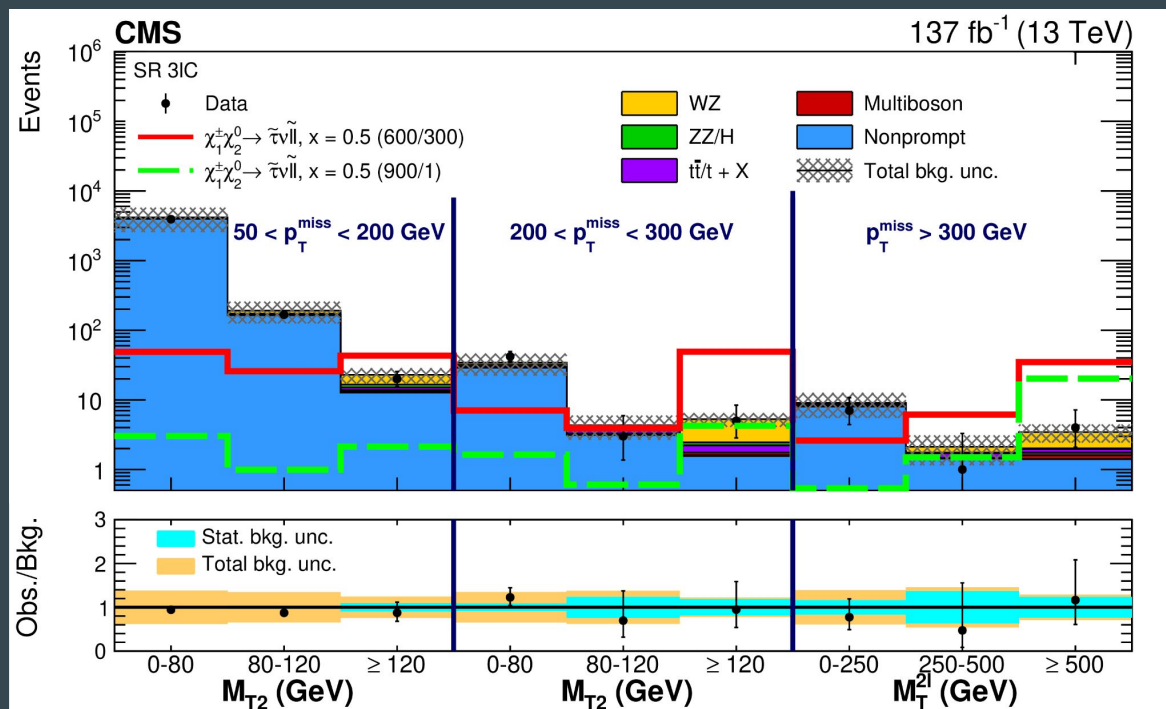


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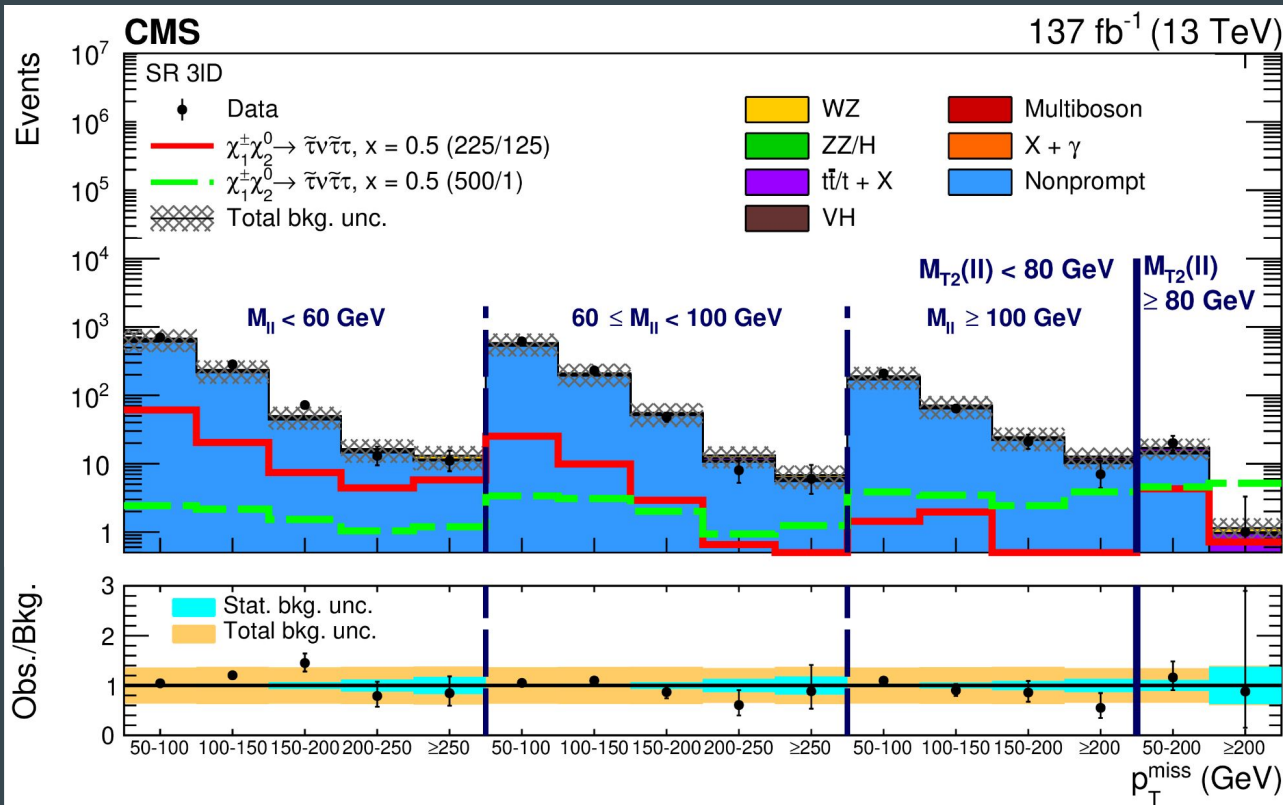
3 light leptons
No OSSF pair
"3lB"



3 leptons: 2 OSSF light leptons + 1 tau



SUS-19-012: Search Regions



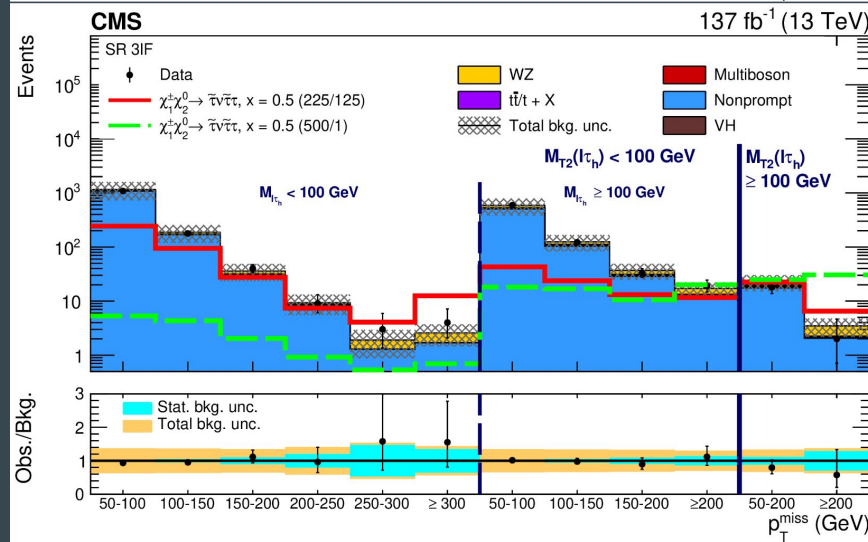
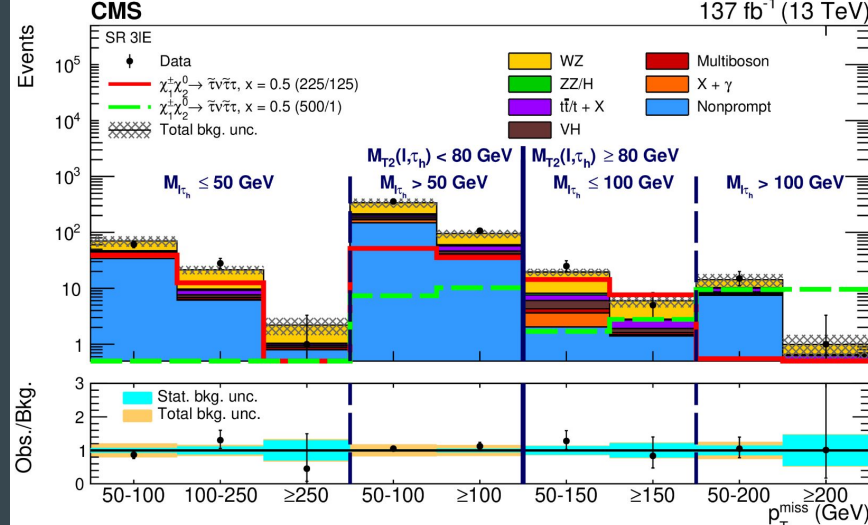
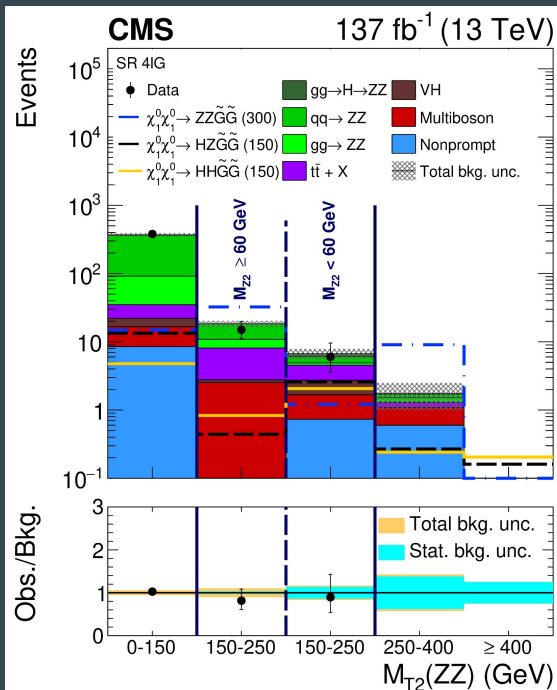
3 leptons:
2 OSOF light
leptons +
1 tau

SUS-19-012: Search Regions

4 leptons,
2 OSSF pairs

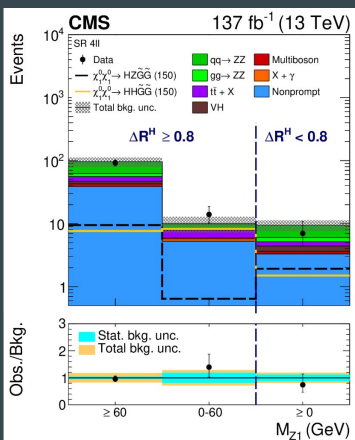
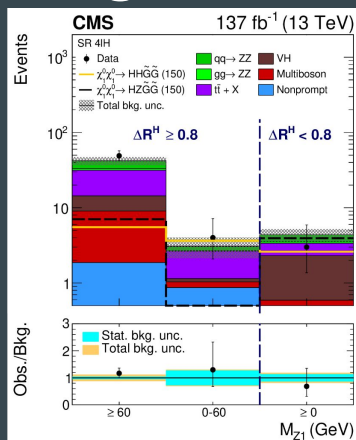
3 leptons:
2 SS light
leptons + 1
tau

3 leptons:
1 light
lepton
2 tau



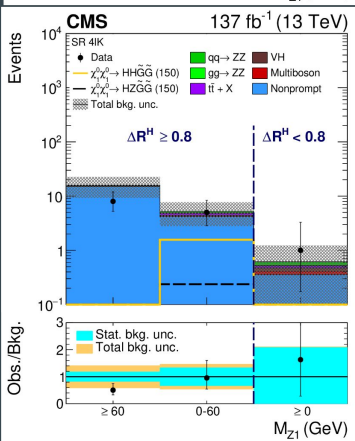
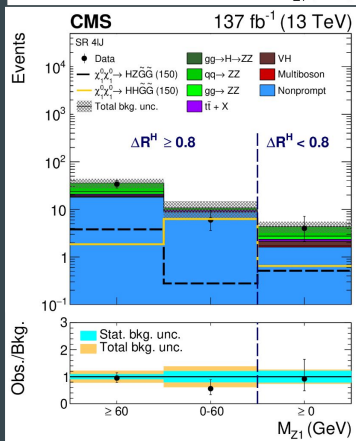
SUS-19-012: Search Regions

4 light leptons,
no OSSF pairs



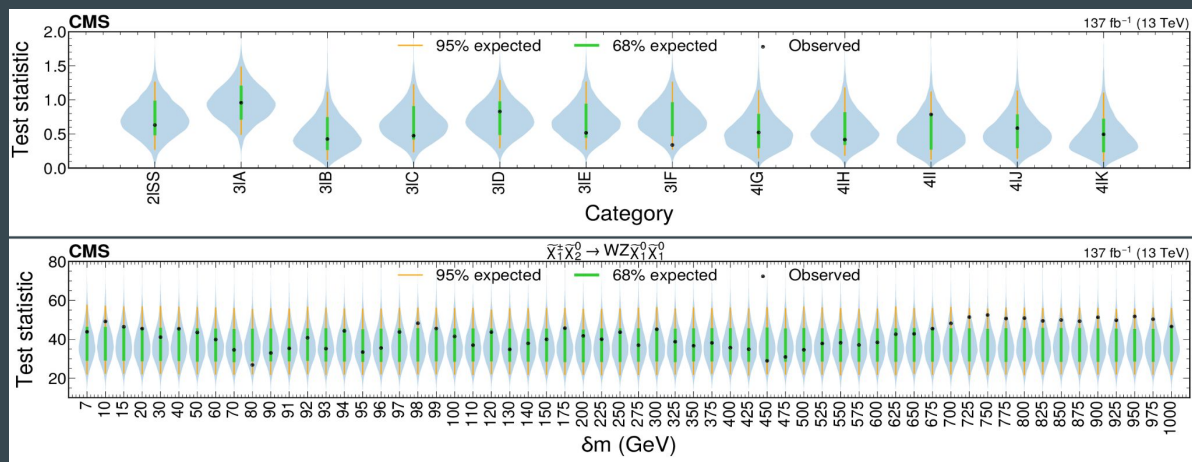
3 light leptons + 1 tau

2 light leptons + 2
tau
2 OSSF



2 light leptons +
2 tau
1 or less OSSF

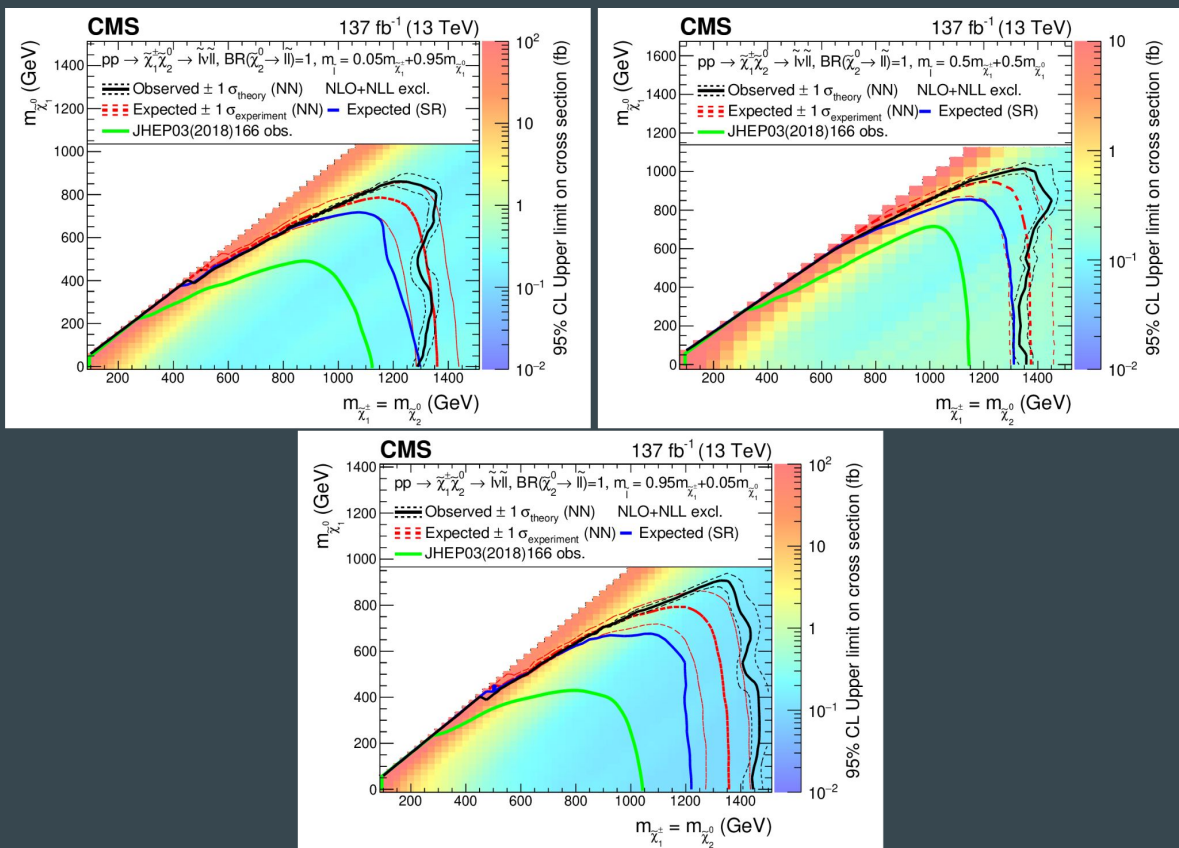
SUS-19-012: Results



No significant **excess** observed:

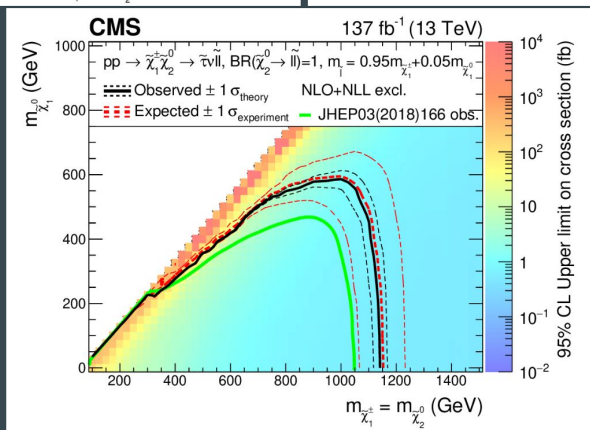
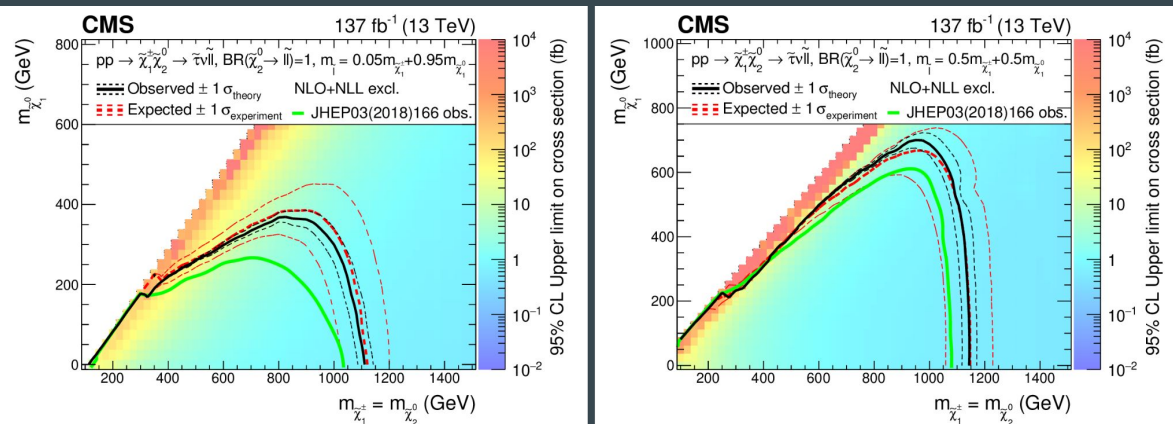
- Shaded area:
Expected test statistic distributions from background-only fit
- Points:
Observed test statistic

SUS-19-012: Interpretation



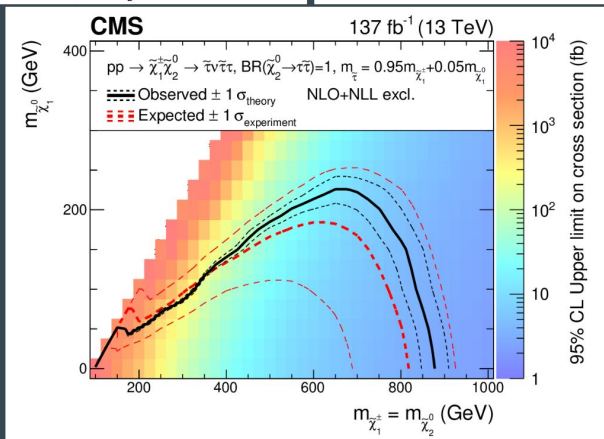
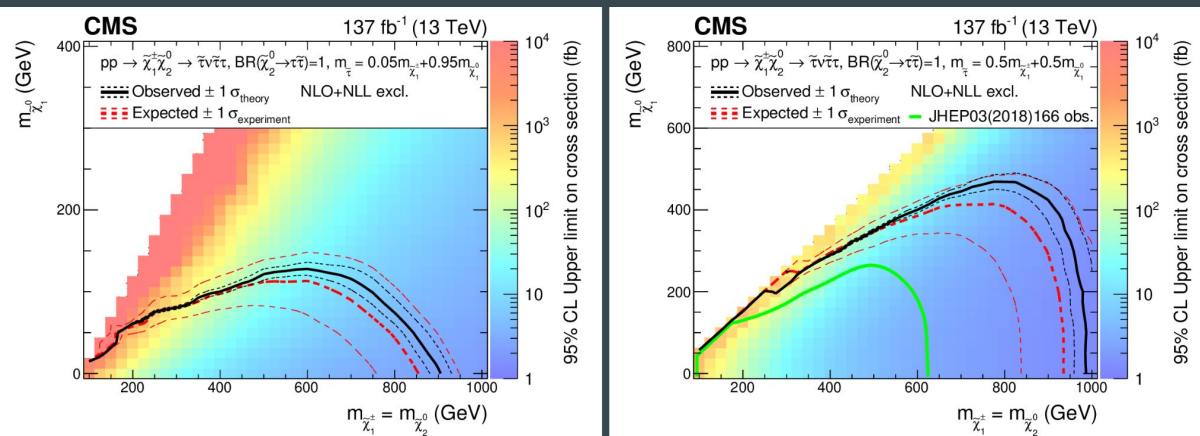
Slepton-mediated
flavor democratic
decays

SUS-19-012: Interpretation



Slepton-mediated
tau-enriched decays

SUS-19-012: Interpretation



Slepton-mediated
tau-dominated
decays

SUS-19-012: Interpretation

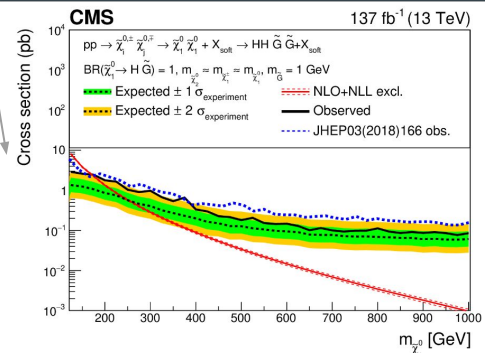
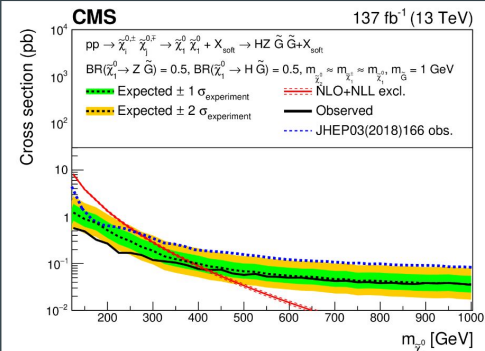
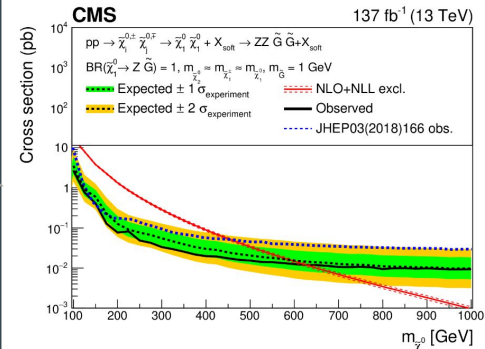
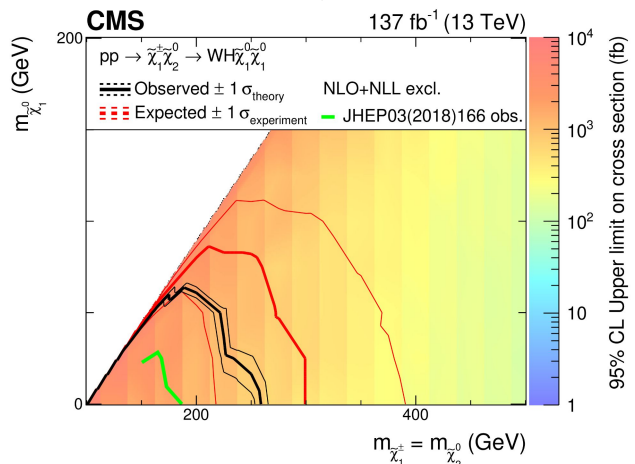
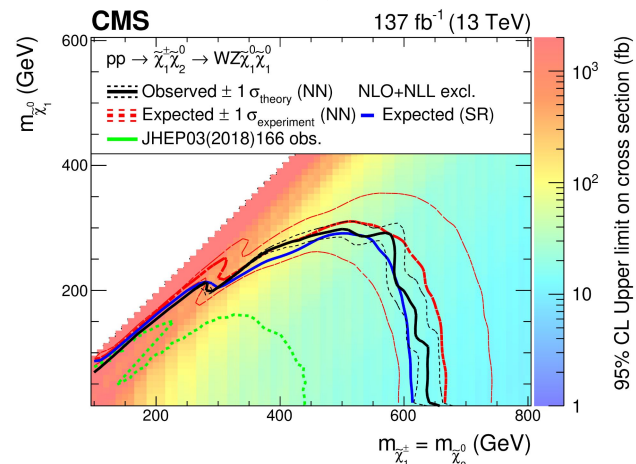
WZ-mediated decay

WH-mediated decay

GMSB ZZ decay

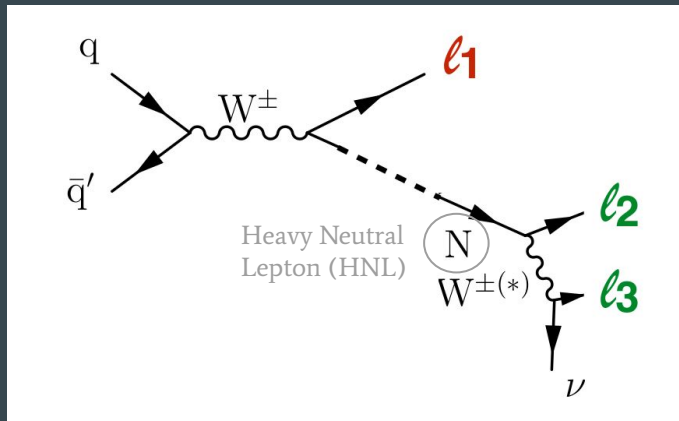
GMSB HZ decay

GMSB HH decay



Heavy Neutral Leptons

- No direct interactions with sterile HNL
- Interactions through mixing of HNL with SM neutrinos



- HNL production in decays of W bosons
- Depending on the mass of the HNL, different scenarios arise

Low Mass: $m(N) < m(W)$
 W from HNL decay off-shell

- $1 \text{ GeV} < m(N) < 15 \text{ GeV}$:

$$\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$$

→ Long-lived HNL
 → Displaced Leptons

- $10 \text{ GeV} < m(N) < 80 \text{ GeV}$:
 Prompt HNL

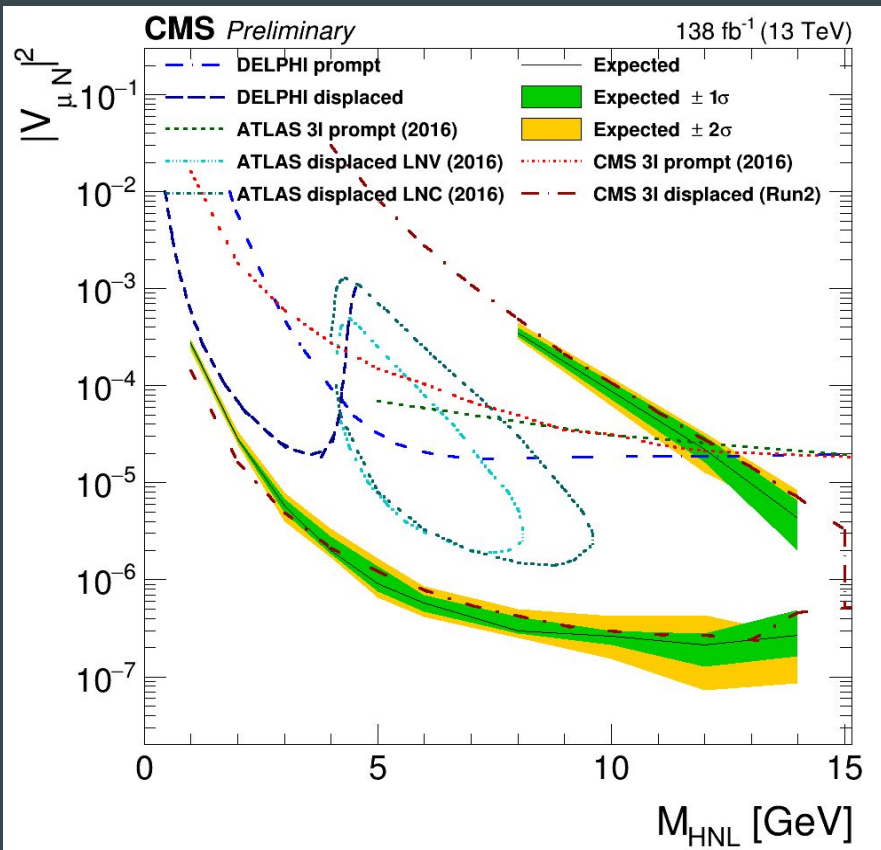
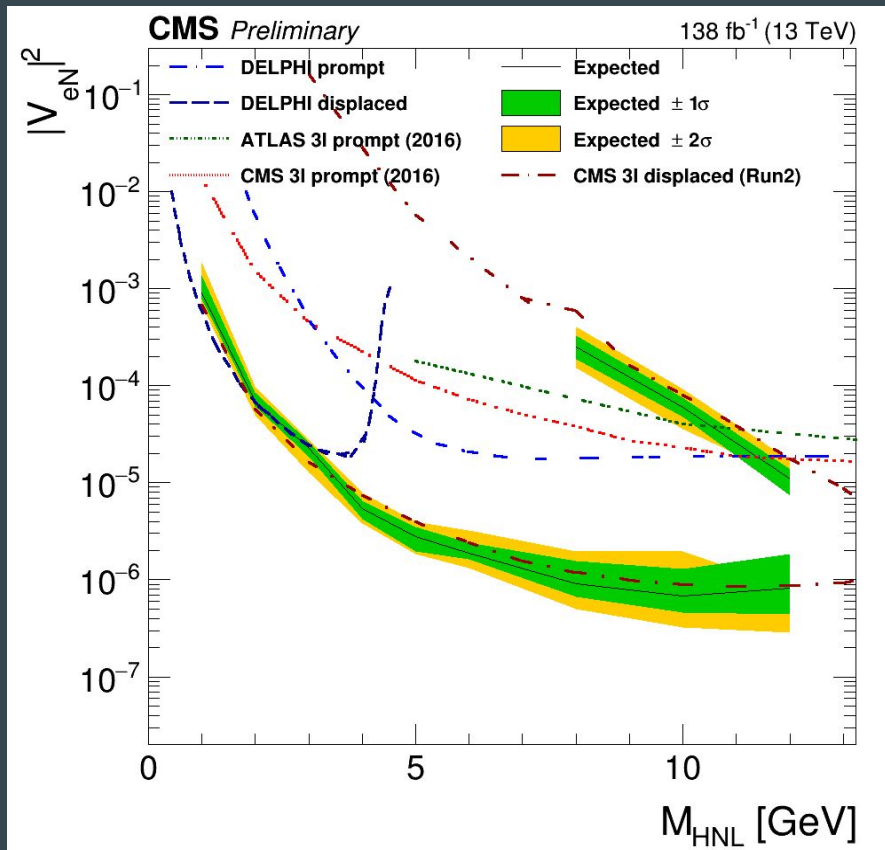
High Mass: $m(N) > m(W)$
 First W off-shell

- $80 \text{ GeV} < m(N) < 1500 \text{ GeV}$

Ongoing Full Run II HNL analyses:

- **Long-lived** HNL (displaced)
 - **Trilepton** final state ([EXO-20-009](#))
 → UGent
 → Results are public and about to publish
 - **Two same sign lepton** final state ([EXO-21-011](#))
 → UGent, UCL, Antwerp
 → Almost final
- **Short-lived** HNL (prompt): UGent-ULB
 - Previous iteration with 2016 data:
 - Now adding **tau coupling!**

Displaced dilepton analysis: expected limits



Displaced trilepton analysis: limits

